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RESEARCH ON THE INTERNATIONAL SPACE STATION: UNDERSTANDING FUTURE POTENTIAL FROM CURRENT ACCOMPLISHMENTS

Judy M. Tate and Tracy L. Thumm

Engineering and Science Contract Group, Houston, TX, U.S.A.
judy.tate-1@nasa.gov, tracy.thumm-1@nasa.gov

Roger H. Weiss

Science Applications International Corporation, Houston, TX, U.S.A.
roger.h.weiss@nasa.gov

Julie A. Robinson

NASA Johnson Space Center, Houston, Texas, U.S.A.
julie.a.robinson@nasa.gov

ABSTRACT

In November 2007, the International Space Station (ISS) will have supported seven years of continuous presence in space, with 15 Expeditions completed. These years have been characterized by the numerous technical challenges of assembly as well as operational and logistical challenges related to the availability of transportation by the Space Shuttle. During this period, an active set of early research objectives have also been accomplished alongside the assembly. This paper will review the research accomplishments on the ISS to date, with the objective of drawing insights on the potential of future research following completion of the ISS assembly.

During the first seven years and fourteen Expeditions to the International Space Station (ISS), several events shaped the focus of research on the ISS and the ability of the ISS for performing early research. NASA's research on ISS has continued and adapted through these events.

The *Columbia* accident which occurred in 2003, during Expedition 6, halted assembly of the ISS, the Space Shuttle fleet was grounded, and led to the temporary reduction in number of crewmembers from three to two [1].

The objectives for NASA research on the ISS have also changed strategically to support the *Vision for Space Exploration* announced by the U.S. President on January 14, 2004 [2]. While still including some physical and biological investigations, emphasis for NASA-funded research activities has shifted from fundamental studies of space phenomena to programs

targeted at reducing the risks to exploration missions to the Moon, Mars, and beyond [1].

By the end of Expedition 15 in November 2007, an expected 121 U.S.-integrated investigations will have been conducted on the ISS, with 91 of these completed. Many of these investigations include multiple scientific objectives, with an estimated total of 334 scientists served. Through August 2007, 106 scientific publications have been identified. Another 184 investigations have been sponsored by the ISS international partners, which independently track the scientists they have served and results publications.

Through this survey of U.S. research completed on ISS, three different themes will be addressed:

- (1) How have constraints on transportation of mass to orbit affected the types of research successfully completed on the ISS to date?

What lessons can be learned for increasing the success of ISS as a research platform during the period following the retirement of the Space Shuttle?

- (2) How have constraints on crew time for research during assembly and the active participation of crewmembers as scientists affected the types of research successfully completed on the ISS to date? What lessons can be learned for optimizing research return following the increase in capacity from 3 to 6 crewmembers (planned for 2009)?
- (3) What do early research results indicate about the various scientific disciplines represented in investigations on ISS? Are there lessons specific to human research, technology development, life sciences, and physical sciences that can be used to increase future research accomplishments?

CONSTRAINTS ON MASS TO ORBIT

Science on the ISS has been affected by the constraints on transportation of mass to orbit between 2003 through 2005 due to the temporary halt of Space Shuttle flights.

During the Space Shuttle Program hiatus, the NASA relied on the Russian Soyuz and Progress vehicles to transport U.S. crewmembers and supplies. The limited U.S. allocations on the vehicles prevented transportation of large items such as research racks and major new equipment for experiments. Figure 1 shows the decrease in upmass to the ISS during Expeditions 6–12; the decrease was a direct result of the grounding of the Space Shuttle fleet.

To continue performing science investigations on the ISS, a call was issued to the science community to develop experiments which required little to no upmass [3A]. Six low upmass (generally handheld) investigations were delivered to the ISS, BCAT-3, CFE, DAFT, Foam, SNFM and Yeast-GAP; four investigations were added to the ISS Research Program complement of investigations using items already on board the ISS, CBOSS-FDI, FMVM, ISSI, MFMG and one investigation was

expanded beyond its original activities, EPO (Table 1). The ADUM experiment, using ultrasound hardware already on orbit and only requiring launch of a training CD, was also accelerated during this period. These investigations allowed for maximum use of the crew time available on ISS Expeditions 7–11 (the Space Shuttle Program returned to flight on July 26, 2005, during Expedition 11).

During Expedition 11, flight STS-114/LF1 in July 2005 resumed construction of the ISS; Expedition 13 in 2006 saw the first substantial increase in upmass for research since Expedition 5 in 2002 (Figure 1). Three facilities were launched during this time: European Modular Cultivation System (EMCS), Minus Eighty Laboratory Freezer for ISS (MELFI), and Portable Glovebox (PGB). With these new facilities, new capabilities for a variety of experiments were available to researchers.

As Expedition 16 approaches, the ISS Research Program will see the largest amount of upmass allocated for payloads to the ISS to date. This increase will be driven by the launch of the European *Columbus* module (planned for December 2007), and then followed over the next year by the Japanese laboratory modules and facilities, and the remaining NASA research facilities.

Results of low-upmass experiments

Detailed descriptions of the low upmass experiments in Table 1 are available in [3, 4]. Here, we summarize the results as an indicator of the success of this strategy during shuttle downtime.

The *In Space Soldering Investigation (ISSI)* examined how microgravity affected various aspects of soldering such as joining techniques, shape equilibrium, wetting phenomena, and micro-structural development. Using a soldering iron, wire and solder, crewmembers created coupons by wrapping the solder around the wire and then melting the solder by touching the wire with the soldering iron. Results provided information on the underlying

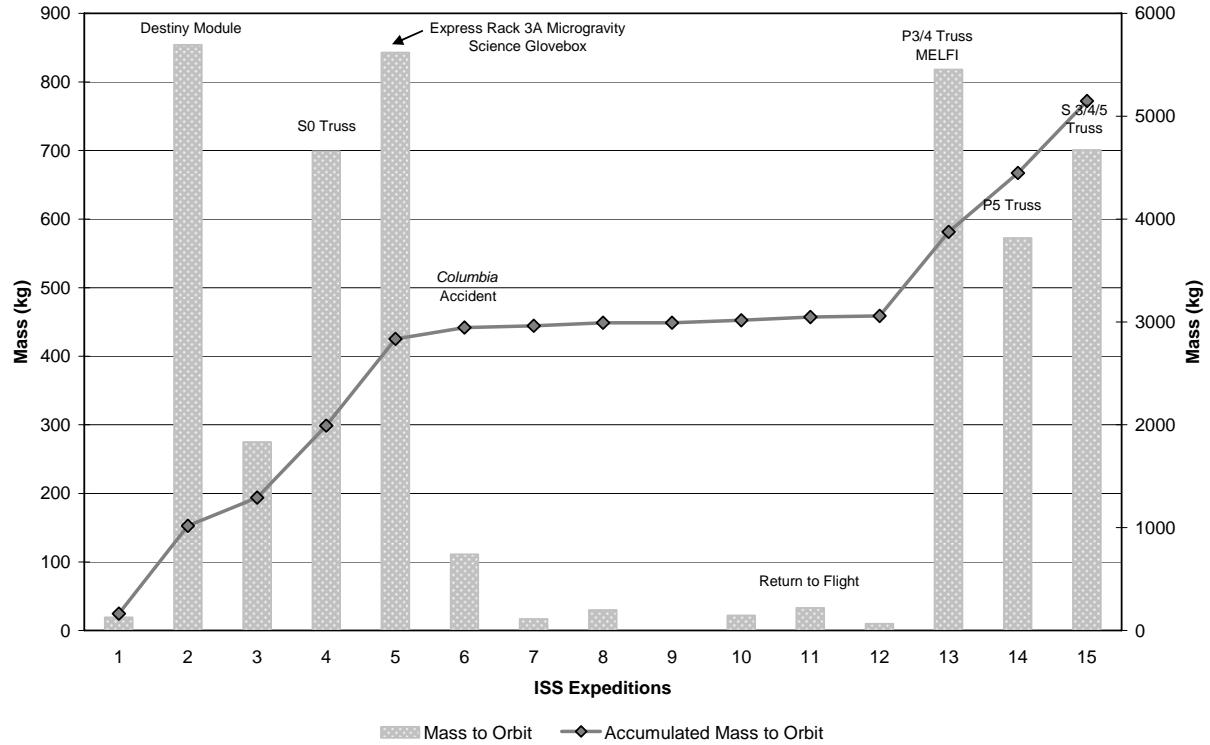


Figure 1: Research equipment and samples transported the ISS during Expeditions 1–15; the plateau between Expeditions 6–11 is a direct result of the grounding of shuttle flights to the ISS [3, 4], data as of July 2007.

Investigations [see details in 3]	Scientific Discipline(s)
ADUM (Advanced Diagnostic Ultrasound in Microgravity)	Human Research and Countermeasure Development
BCAT-3 (Binary Colloidal Alloy Test – 3)	Physical and Biological Sciences in Microgravity
CBOSS-FDI (Cellular Biotechnology Operations Support Systems: Fluid Dynamics Investigation)	Physical and Biological Sciences in Microgravity
CFE (Capillary Flow Experiment)	Technology Development
DAFT (Dust and Aerosol Measurement Feasibility Test)	Technology Development
EPO (Education Payload Operations)	Observing the Earth and Educational Activities
FMVM (Fluid Merging Viscosity Measurement)	Physical and Biological Sciences in Microgravity
Foam (Viscous Liquid Foam - Bulk Metallic Glass)	Physical and Biological Sciences in Microgravity
ISSI (In Space Soldering Investigation)	Technology Development
MFMG (Miscible Fluids in Microgravity)	Physical and Biological Sciences in Microgravity
SNFM (Serial Network Flow Monitor)	Technology Development
Yeast-GAP (Yeast-Group Activation Packs)	Human Research and Countermeasure Development

Table 1: Low-upmass ISS investigations implemented following the *Columbia* accident.

cause of poor soldering performance in space, and gave new information about the behavior of rosin in microgravity soldering [5]. Based on these results a follow-on technology test with externally applied rosin was recently completed on ISS (Soldering in Reduced Gravity Experiment, SDTO 17003-U) in order to learn the best way to perform future repairs.

The *Capillary Flow Experiment* (CFE) arrived on the ISS during Expedition 9 and is scheduled to continue through Expedition 16. The experiment evaluates three different types of fluid physics phenomenon in microgravity: fluid interaction with a contact boundary condition, capillary-driven flow in interior corner networks, and critical wetting phenomena in complex geometries. The fluid used in the specially designed handheld devices is silicone oil that is disturbed by either the crewmember tapping on the side or moving the vane inside the container. The data that is gathered from this experiment will be used in the design of future fluid systems that may potentially be used in new spacecraft fuel tanks. As with several other handheld investigations, observations made by the crewmembers as they operated the experiment have led to runs with additional parameters. Sessions of this experiment are still being conducted, but interim results show new fundamental measurements of capillary flow parameters [6].

Advanced Diagnostic Ultrasound in Microgravity (ADUM) was completed from on Expeditions 8–11. It demonstrated that minimal training along with audio guidance from a certified sonographer can produce ultrasound imagery of diagnostic quality. The work has important applications for emergency medicine on Earth, and in future exploration missions [7]. The ISS crewmembers, acting as operators and subjects, have completed comprehensive scans of the cardiothoracic and abdominal organs as well as limited scans of the dental, sinus, and eye structures. They also have completed multiple musculoskeletal exams, including a detailed exam of the shoulder muscles. [8].

One conclusion to draw from the success of these low-upmass experiments is that, with or

without complex hardware, the study of physical processes in the absence of gravity is young. Relatively simple experiments can generate significant new data. As more sophisticated physical science equipment becomes available in the next few years, the potential for new physical insights from microgravity research on ISS research will be significant.

Future upmass limitations

Once the Space Shuttle fleet is retired in 2010, the challenge of sending new science facilities and investigations to the ISS will present itself again. One important lesson that came from the three year period of limited transportation was that small, fundamental experiments can be successfully developed and executed.

In order to increase the success of the ISS as a research platform after Shuttle retirement investigators will need to rely on other forms of transportation such as the Russian Progress vehicles, the next generation of U.S. transportation vehicles (Commercial Orbital Transportation Services, and *Orion*), the European Space Agency Automated Transfer Vehicle (ATV) and the Japan Aerospace and Exploration Agency H-II Transfer Vehicle (HTV). The investigators will need to develop experiments that can fit the space constraints and can provide the maximum science output for their theories.

The suite of laboratory facilities to be launched as part of the completion of ISS is an important asset as in many cases samples can be launched with relatively low upmass, and more sophisticated experiments can be completed with on orbit measurements and data downlink. Being able to make on-orbit measurements also reduces (but does not eliminate) the need for downmass which will also be a challenge after 2010. The Space Shuttle hiatus, from 2003 – 2005 has shown that upmass and downmass limitations can be overcome to insure successful science under changing availability of transportation to orbit.

CONSTRAINTS ON CREW TIME

During the early years of the ISS assembly, Expeditions 0–6, crew time for the ISS investigations was highly constrained by the requirements of ISS assembly and maintenance [9]. The decrease in crew size, which began during Expedition 7, in 2003 [1], also reduced

the number of early science investigations completed compared to prior plans [10]. These constraints can be seen in Figure 2. Even with return to a 3-person crew in September 2006, crew time has remained a limiting factor during ISS assembly.

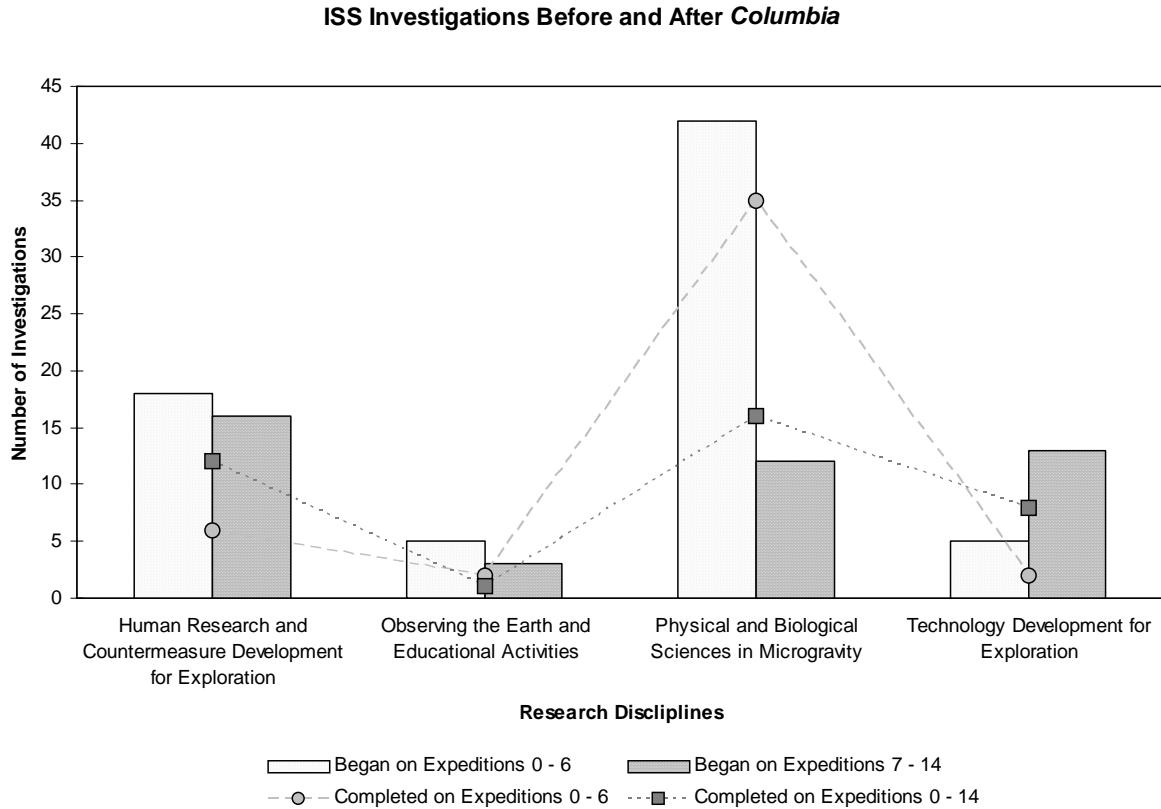


Figure 2: Comparison of the ISS investigations begun and completed before and after the *Columbia* accident on February 1, 2003.

ISS research before the *Columbia* accident included a high proportion of investigations of physical and biological sciences in microgravity (Figure 2) compared to the other research disciplines. Part of this was because large numbers of investigators shared hardware with simultaneous operations in fields such as protein crystal growth. These had ideal resource requirements for early investigations because large sample sizes and large numbers of studies could be accomplished with the minimal need for crew time for activities such as hardware

transfer, activation and deactivation. Changes in discipline emphasis for NASA's use of ISS can also be seen in the shift from physical and biological sciences to technology development in Expeditions 7-14.

Additional crew time for research has been obtained during these early ISS expeditions in two very different ways. The first is through additional accomplishments of the ISS crew beyond their scheduled work days, and the second is by optimizing research planning to

take advantage of any changes in launch schedules or assembly by completing additional research objectives.

Saturday Science

Astronaut Don Pettit initiated Saturday Science to complete a series of educational demonstrations and microgravity experiments during Expedition 6 [3]. The idea of using Saturday free time to complete additional ISS research experiments was initiated by astronaut Michael Fincke on Expedition 9. Since the start of Saturday Science activities, an increase in crew time for ISS research has been recorded in all expeditions in which Saturday Science activities were performed (Figure 3). Expedition 9 saw nearly 30% of its total crew time for investigations performed using Saturday Science crew time (Figure 3).

Number of Crew

A slight increase in crew time was observed in Expedition 14 compared to previous

expeditions, even though major assembly activities also resumed during this period. The increase occurred partly because of the increased number of crewmembers (from two back to three), and partly because NASA took advantage of delays in Shuttle flights to add research back into the expedition (Figure 3). Expeditions 1–6 were composed of three crewmembers, Expeditions 7–13 were composed of two crewmembers; the ISS crew was expanded back to three crewmembers at the end of Expedition 13.

The ISS will be expanded to six resident crewmembers in April 2009. From that date until ISS assembly is complete, utilization will still be constrained by assembly and maintenance tasks. Once assembly is complete, doubling the number of crewmembers onboard, doubling the crew size to six is expected to allow on the order of 4 times the crewtime for research.

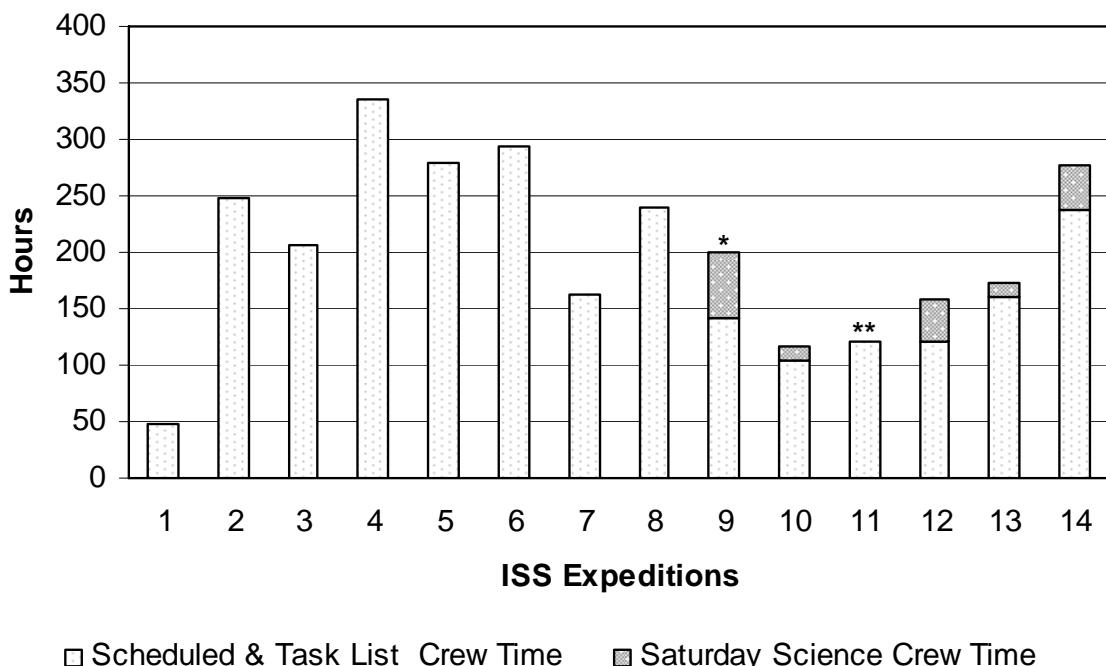


Figure 3: Scheduled crew time hours and Saturday Science crew time hours for Expeditions 1–14. *Saturday Science activities began during Expedition 9. **No Saturday Science activities were performed during Expedition 11. Dates of the expeditions are shown in the Appendix.

Reserve Investigations

In addition to the investigations that were scheduled for operation, each expedition plan also included “on-orbit reserve” investigations. These are investigations that have all necessary equipment on orbit, but are not scheduled due to crew time limitations. Reserve investigations have been activated during many ISS expeditions.

For example, the launch delay of STS-117/13A from March 2007 to June 2007 allowed for the performance of several reserve investigations. Three activities, Capillary Flow Experiment (CFE), Lab-on-a-Chip Application Development-Portable Test System (LOCAD-PTS) and Education Payload Operations (EPO) were not originally scheduled for operation during Expedition 14, but were able to be performed because of the additional time received following the launch delay. In addition, two investigations, Earth Knowledge Acquired by Middle Schools (EarthKAM) and Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES) obtained additional sessions due to the launch delay [11].

EARLY RESEARCH RESULTS

NASA ISS investigations conducted through Expedition 14 have laid the groundwork for research planning for the expeditions to come. Crewmembers are performing scientific investigations on the ISS, while building and maintaining a livable habitat, serving as a model for the goals of future exploration missions. The success of a wide variety of investigations is an important hallmark of early research on the ISS. Full lists of experiments and results publications are maintained by NASA at

http://www.nasa.gov/mission_pages/station/science/

The investigations fall into four broad disciplinary categories [2]:

- **Human Research and Countermeasure Development for Exploration**—human medical research to develop the knowledge needed to send humans on Exploration missions beyond Earth orbit.
- **Technology Development for Exploration**—studies test and establish new

technologies for use in future Exploration missions.

- **Physical and Biological Sciences in Microgravity**—studies of physics, chemistry, and, biology using microgravity conditions to gain insight into physical processes and the effect of the space environment on living organisms.
- **Observing the Earth and Educational Activities**—these activities and investigations allow students and the public to connect with the ISS mission, inspire students to excel in science, technology, engineering and math, and share the crewmembers’ unique view of the Earth system with scientists and the public.

Of the NASA-integrated investigations performed through Expedition 14, 81 have been completed and five—which were begun in early ISS expeditions—will continue through the life of the ISS (Figure 4). We have identified 102 publications from these activities. The number of human research investigations completed to date is slightly lower than the number of physical sciences investigations. The number of technology development and education and observing the Earth investigations is less than the number of physical and biological investigations (Figure 4).

Investigations in human research must be carried out using statistically significant numbers of human subjects in order to draw appropriate conclusions. Crewmembers can generally participate in, at most, six different investigations per expedition [12]. The grounding of the Space Shuttle fleet caused a decrease in the ISS crew size (see Appendix); this decrease in availability of subjects limited the rate at which human research investigations were completed on the ISS. The shift back to a crew of three in September 2006 and the potential for larger crew complements in 2009 are important factors for obtaining sufficient numbers of human subjects for investigations (Figure 5). Of the 34 NASA human research and countermeasure development investigations on ISS to date, 23 used humans as subjects; 10 have been completed and we identified a total of 29 scientific publications.

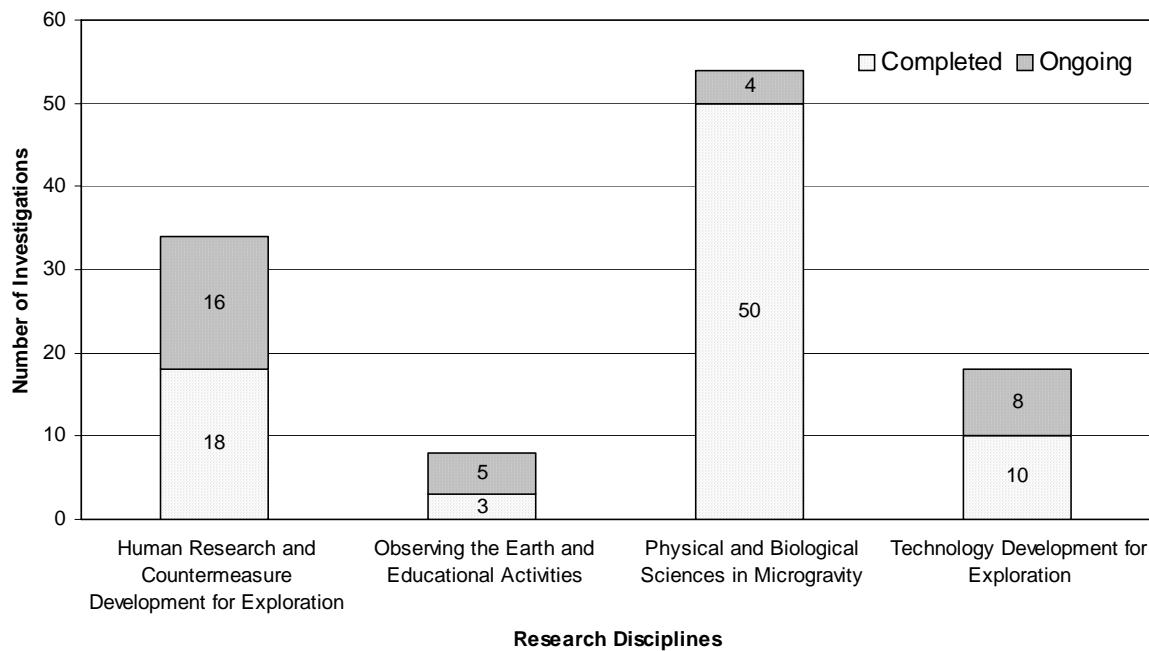


Figure 4: ISS research investigations through Expedition 14, by broad research disciplines. The graph includes both completed and ongoing investigations in each research discipline. Investigations are defined as a research effort led by a defined group of investigators and hardware with a set of research objectives.

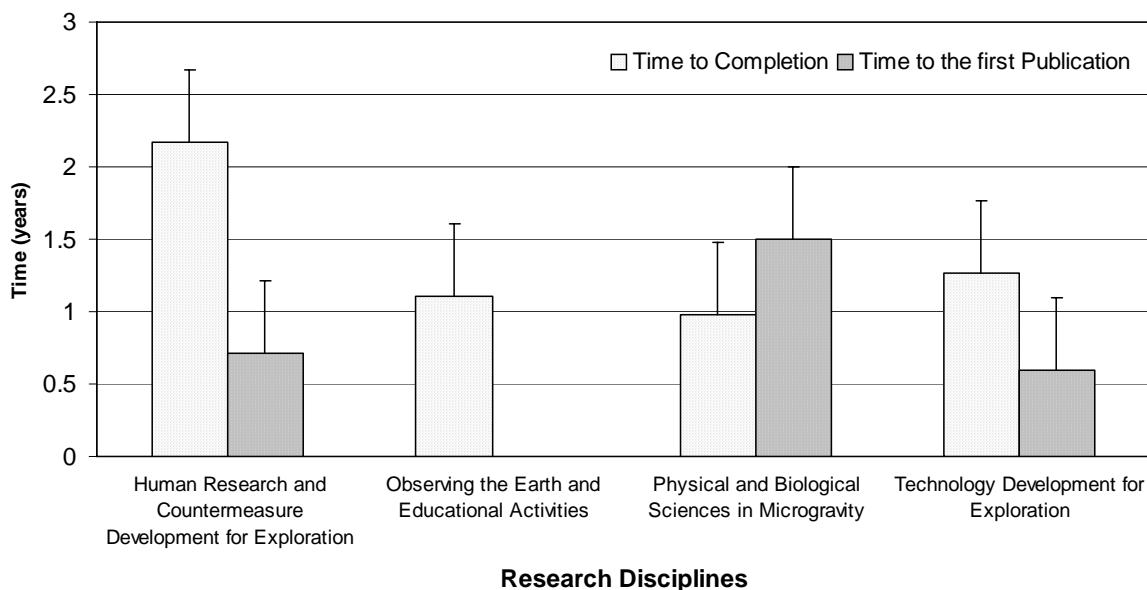


Figure 5: Time to Completion vs. Time to the First Publication for ISS investigations completed to date, means and standard deviations shown. Ongoing activities with no completion date are not shown.

Eighteen technology investigations have been performed on the ISS through Expedition 14, ten have been completed (Figure 5), and we identified 16 results publications. Future exploration—the return to the Moon and human exploration of Mars—presents many technological challenges. Studies on the ISS can test a variety of technologies, systems, and materials that will be needed for future Exploration missions [2].

Through fourteen ISS Expeditions, eight education and observing the Earth investigations have been performed, with a total of 13 publications. Three of these “investigations” are actually umbrella activities serving numerous educators or scientists and will continue for the life of the ISS. The ISS educational activities have had a positive impact on students by involving them in the ISS research, and by using the ISS to teach them the science and engineering behind space exploration and a 2006 survey identified that over 30 million students worldwide had the opportunity to participate in

some sort of educational activities from the ISS [13].

The potential value of the ISS as an Earth observing platform is illustrated by the scientific publications and uses of astronaut photography taken from ISS [14, 15]. Through August 2007, over 286,000 photographs of Earth had been taken by crewmembers onboard the ISS; each month 300,000 to as many as 2 million images were viewed or downloaded from the Gateway to Astronaut Photography of Earth website (<http://eol.jsc.nasa.gov/>). Launch of NASA and international partner facilities and several different multi- and hyperspectral instruments to support remote sensing using ISS as a platform are planned for 2007–2009. Early results from these instruments will serve as pathfinders for future use of internal and external ISS facilities for Earth science observations.

Fifty-four physical and biological investigations have been performed through Expedition 14 on the ISS and 50 have been completed (Figure 4), with 44 publications in this area to date.

Summary of ISS Research Productivity

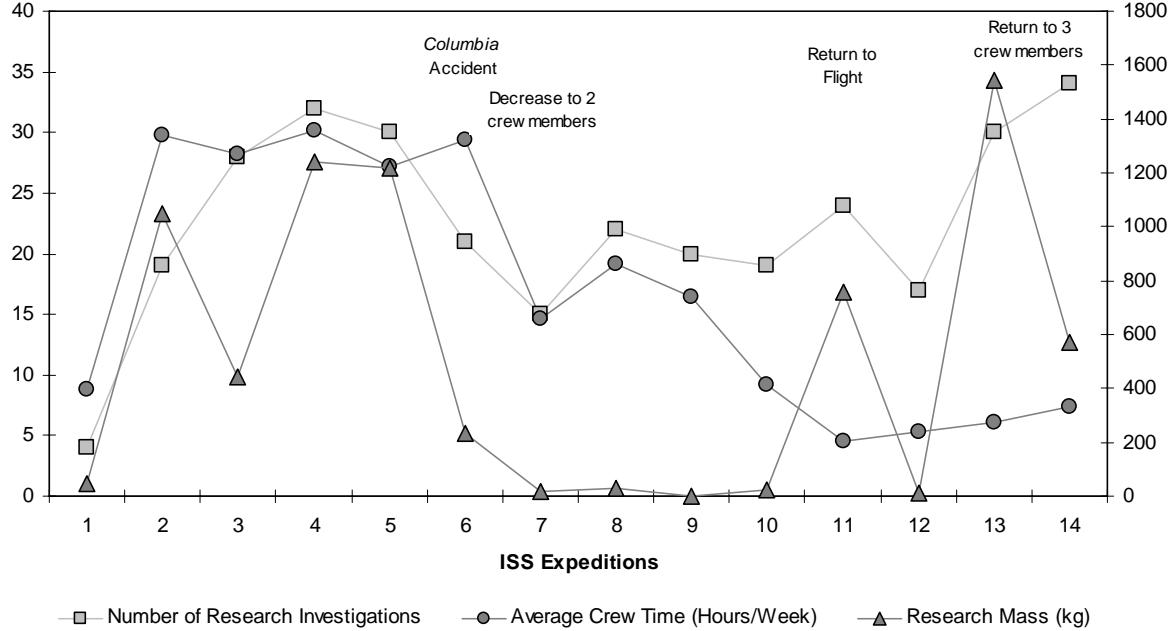


Figure 6: Summary of ISS Research Productivity, graph illustrates the number of investigations, the average crew time (hours/week) and research mass to orbit from Expeditions 1–14

Typically, these investigations comparatively greater equipment mass to be sent to the ISS, but often required less crewtime than investigations in other areas. Once on the ISS, the design of these investigations allowed for a large sample size to be tested during a short period of time in the microgravity environment and ensured a shorter time to completion (Figure 5).

Early ISS research results have indicated that although human research investigations take longer to complete the time to publication following completion is relatively short (< 1 year); which means that the time period to convert a research investigation into medical protocols for crewmembers on long duration missions beyond low Earth orbit is relatively rapid compared to the time to complete the experiment. Physical and biological investigations have a relatively short average completion time (< 1 year), but it may take longer to publish results, this is believed to be due to the large sample size that must be analyzed following return to Earth. Technology development investigations on average take a little over a year to complete but have publications in less than a year, this is due to the design of most of the investigations in this category which allows for downlink of data from the ISS while the investigation is ongoing data analysis is occurring on Earth.

DISCUSSION

Research has been conducted and completed on the ISS under a set of challenging constraints during the past 7 years. This paper has reviewed the ways in which research has been completed on ISS during assembly (Figure 6). ISS researchers and implementers have been adaptable to the changing landscape of resource availability. At different times crewtime, upmass, and downmass have each impacted early research experiments, but the diversity of types of experiments has allowed optimization and continuation of research and led to a growing body of scientific publications.

The objective of this review of accomplishments was to derive lessons from early utilization that can be of benefit to NASA and other agencies as

they plan for research on ISS after assembly is complete. These lessons can be grouped into several different areas.

Resource flexibility—Unexpected operational challenges can affect the resources available to complete experiments. By having a research program with a mix of resource needs for different experiments, it is possible to maintain scientific return under a variety of circumstances. An ideal research portfolio includes some experiments that are automated and others that can benefit from extra crew time. Having a few experiments available that require little upmass and take advantage of hardware and materials already on orbit can help protect for difficulties in launch schedules. These flexibilities will continue to be important with new vehicles providing upmass and downmass after the retirement of the Space Shuttle?

Crewtime planning—Although automated experiments may seem to be a way to avoid limitations on crewtime available for research, early ISS research has benefited a number of times from observations made by the crewmembers while carrying out the experiment. These observations sometimes have led to additional test runs, and crewmembers have responded collaboratively by volunteering time to achieve extended objectives. The stockpiling of “reserve” experiments has also allowed use of crew time that becomes available unexpectedly—either due to changes in operational schedules or the operation of other experiments. Such techniques should continue to be used throughout the life of ISS.

Research disciplines—In the major areas of research, both basic and applied work have produced results over the seven years of ISS utilization to date. Discipline-specific differences in ISS research have related only to realistic definition of duration and time to publication.

The presence of a long-duration high-capability platform in microgravity facilitates experiments that have not been possible in orbit before. Even some of the simplest physical experiments on ISS have led to unanticipated results. Applied

ISS research on human health and space technology has already begun to change the way that NASA designs, builds, and operates long-duration space missions.

The history of research accomplished on the ISS during assembly serves as an indicator of the value and potential of the ISS when full utilization begins. In many ways the early research experience during ISS assembly has also prepared NASA for research on future exploration missions where the supply capability will be limited by distance. NASA and international group of ISS partners will soon have research facilities in position to initiate full research utilization. As assembly progresses, the ISS is emerging as a multidisciplinary platform with nearly unbounded potential for gaining knowledge.

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APPENDIX

Expedition	Dock Date (MM/DD/YY)	Undock Date (MM/DD/YY)	# Crew
One	11/02/00	03/18/01	3
Two	03/10/01	08/20/01	3
Three	08/12/01	12/15/01	3
Four	12/07/01	06/15/02	3
Five	06/07/02	12/02/02	3
Six	11/25/02	05/03/03	3
Seven	04/28/03	10/27/03	2
Eight	10/20/03	04/29/04	2
Nine	04/21/04	10/23/04	2
Ten	10/15/04	04/24/05	2
Eleven	04/16/05	10/10/05	2
Twelve	10/03/05	04/08/06	2
Thirteen	04/01/06	09/28/06	2-3
Fourteen	09/20/06	04/21/07	3
Fifteen	04/09/07	ongoing	3

Appendix: Chronology of expeditions to the International Space Station.

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